DEFORMATION STUDIES OF THE FEMUR UNDER STATIC AND DYNAMIC LOADING

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Anatomists have been especially interested in bone architecture and its functional significance since Herman von Meyer exhibited sections of bones and discussed their trabecular arrangement at a scientific meeting in Zurich in 1867. The demonstrations were seen by Culmann, a Swiss mathematician and engineer, who was impressed by the similarity between the arrangement of the trabeculae and the computed lines of internal stress in similar bodies supporting similar loads. Later he compared the trabecular arrangement in the proximal end of the femur with the calculated lines of maximum internal stress in a Fairbairn crane of similar shape.

Since then the femur, perhaps more than any other human bone, has been used in investigations on the functional significance of bone architecture and mechanics. Samples from it, as well as from other bones, were used by Rauber (1) in determining the compressive, tensile and shearing strength of small bony rods and it was one of the bones whose intact strength was measured by Messerer (2) by placing the bone in a materials-testing-machine and statically loading it to failure.

Wolff also included the femur in his classic paper of 1892 on bone transformation in which the trabecular arrangement of bone is considered to be the result of the stresses and strains to which the bone has been normally subjected and of its function in the living body. This interpretation of the significance of the trabecular arrangement of bone is known as Wolff's Law and, although strongly criticized by some investigators, is still generally accepted as far as its basic principles are concerned.

In more recent times, as discussed by Murray (3), the femur has been used in many studies on the development, architecture and mechanics of bone. Koch (4) made a thorough mathematical analysis of 75 cross sections of the femur of a 200 pound Negro male. On this basis he then discussed the functional behavior of the bone in the living body. Milch (5) cut models of the bone out of catalin and, by means of polarized light, studied the stress patterns produced by loading the model. A somewhat similar attempt had previously been made by Roux (cited by Murray) who tried to demonstrate the forces and stresses in bone from deformations produced in a paraffincoated rubber model of the femur.

Such attempts to determine the stresses and strains in bones by means of models are subject to the criticism that they demonstrate the stresses and strains in just two directions in a solid two-dimensional body of homogenous material. Such conditions are quite different from those in a three-dimensional bone composed of heterogenous material. A similar criticism also applies to mathematical calculations of stresses and strains in bone.

In the last two decades industrial techniques have been employed in stuyding deformations in the intact femur. Küntscher (6, 7, 8) coated the femur with melted colophonium and then studied the deformation pattern resulting from static loading of the bone. The technique was based on Hook's Law and the deformation pattern consisted of cracks in the colophonium which arose from tensile deformation in the bone. He (9), as well as Marique (10), also used a Huggenberger extensometer to measure local deformation in the femur.

More recently a similar but a newer industrial technique, the "Stresscoat" Method, has been employed by Evans, Lissner et al (11, 12, 13, 14) in studying femoral deformations under static and dynamic loading of the bone in various orientations.

"Stresscoat" is the trade name for a brittle lacquer, developed by de Forest and Ellis (15), which is used in industry to test for points of weakness and failure in aircraft structures, machinery, etc. The lacquer cracks in response to tensile deformation occurring in the object upon which it is sprayed, the location of the first cracks indicating the point of weakness where failure will occur under sufficient load. The technique is also based upon Hook's Law but has the following advantages over the colophonium method used by Küntscher. 1) "Stresscoat" is much easier to use as it is applied with a spray gun. Consequently it is well impregnated with air bubbles which continually interrupt the cracks in the lacquer thus forcing them to continue in the direction of tensile strain in the underlying bone. This is not true of the colophonium. Although the cracks also arise from tensile strain in the bone there are few air bubbles to interrupt them. Therefore, the cracks, all of which have a high stress concentration at their end, continue to be propagated in their initial direction without regard to the tensile strain in the underlying bone. 2) The "stresscoat" lacquer is also more sensitive than the colophonium and can be applied in a much thinner coat.

"Stresscoat", manufactured by the Magnaflux Corp., Chicago, Illinois, comes in several different numbers and the particular number of lacquer used in a test depends on the temperature-humidity conditions as determined by a wet-dry bulb psychrometer. Steel calibration strips for determining the sensitivity of the lacquer are coated at the same time and kept under the same temperature-humidity conditions until the tests are made. In addition to the degree of local stress concentration the closeness of the cracks in the lacquer depends upon its thickness, the cracks usually being separated by five times the thickness of the lacquer.

The sensitivity of the lacquer, in inches per inch, is determined from the calibration strips at the time of the test. Thus, a lacquer sensitivity of 0.0005 inches per inch means that if an inch of the object being tested, e.g. bone, is stretched as much as 0.0005 of an inch the overlying lacquer will crack in response to the **tensile** stress in the underlying material. Every new crack in the resulting tensile deformation pattern arises in this way. The sensitivity of the lacquer is decreased at higher temperatures and the cracks may close so rapidly that it is difficult to preserve the deformation pattern for future examination. There are different numbered red dye etchants to be used with different temperatures. Thus, with higher temperatures at the time of the test a faster acting etchant is used to preserve the pattern before the cracks have completely closed.

The great value of the "stresscoat" technique in studying bone deformation was first demonstrated by Gurdjian and Lissner (16, 17, 18, 19) in studies of skull deformations and fractures. In order to check the reliability of deformation patterns obtained from cadaver skulls they made three series of "stresscoat" tests on the skulls of six dogs. The first series of tests were on the skull of the living anesthetized dogs, the second series on the skull of the dead dogs with the brain in situ and the third series on the dry skull of the same animals. In each case the deformation patterns obtained, whatever the experimental conditions, were essentially similar, the pattern obtained in the living animal being just slightly more extensive than in the dry skull. The technique was then applied by Evans and Lissner and their associates (loc. cit.) to a study of femoral deformations and fractures in which the mechanical problems, e.g. weight support, muscle action, etc., are quite different from those encounted in the skull. Although the importance of muscle action is fully recognized it was decided to study the femur itself first in order to determine its behavior under static and dynamic loading of the bone in various orientations. Thus the type, point of application, and magnitude of the force, as well as the orientation of the bone, could be controlled in each test.

The material used consisted of 20 femora from adult dissecting room cadavers. The individuals from whom they were obtained ranged from 41 to 81 years of age and were all males. One individual was a Negro, the rest were white. Each bone was tested under static, dynamic and torsion loading in various orientations.

The flesh was removed from the bones and they were also degreased if necessary. They were then sprayed with a thin undercoating of aluminum lacquer to make the cracks in the overlying "stresscoat" lacquer more visible. This was allowed to dry 20 to 30 minutes before the bone was coated with the "stresscoat" lacquer. Steel calibration strips were coated at the same time and kept under the same temperature and humidity conditions. The bones were then allowed to dry for approximately 24 hours before testing. After a test the cracks in the "stresscoat" lacquer were covered with a red dye etchant which, after about a minute, was removed by an emulsifying solution. The dye remains in the cracks and thus makes them more visible. The tensile deformation pattern made by the cracks was then studied with a magnifying glass. For photographing the pattern some of the cracks, generally every third one, were traced with India ink.

The static loading tests were made in a Baldwin-Southwark materials-testing-machine (Fig. 1) calibrated to an accuracy of ½%. The torsion loading tests were made in a torsion machine of a similar degree of accuracy. The dynamic loading tests were made with the apparatus illustrated in Fig. 2.

In the dynamic loading tests the magnitude of the energy dynamically applied to the bone was determined by multiplying the weight of the brass block, 7.9 pounds, by the distance through which it was dropped. The large steel block upon which all or part of the bone rested weights 160 pounds. Brass and steel blocks were used as the amount of energy absorbed by them is negligible. Consequently, virtually all the energy expended in a test was absorbed by the bone. The orientation of the bone and the distance through which the brass block was dropped varied in the different tests. The brass block was released by burning through the supporting cord and was caught by hand on the rebound so that it struck the bone just once.

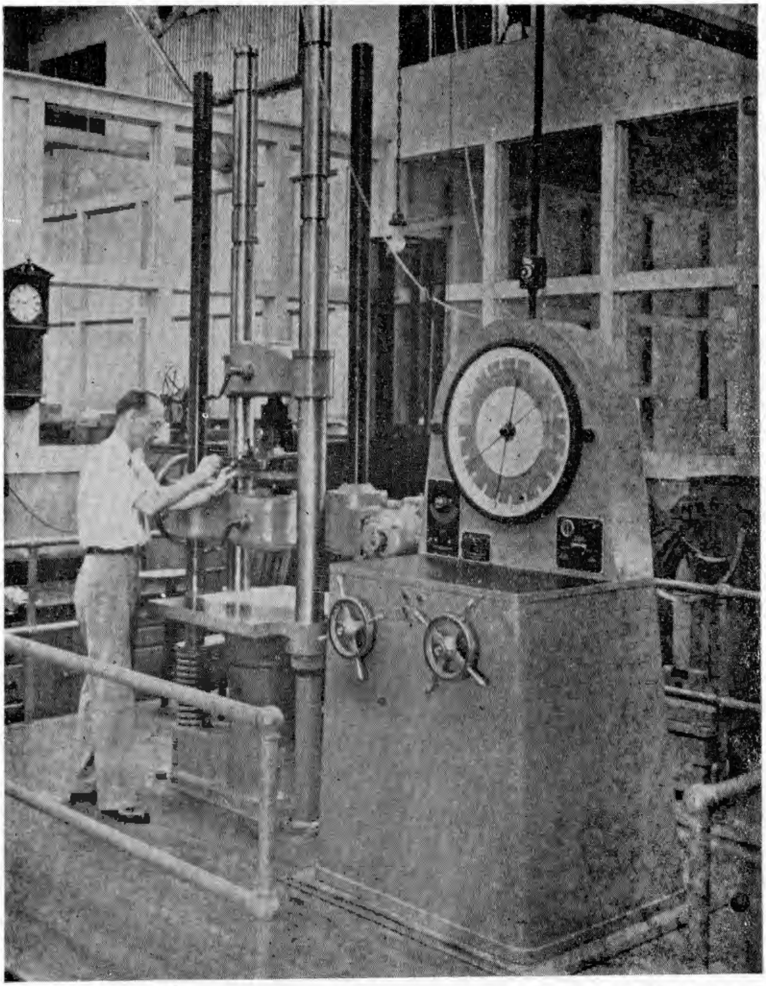

Fig. 1. Type of Baldwin-Southwark materials-testing-machine used in the static vertical and "abduction" loading tests.

Before being tested each bone was weighed and the following measuremente were taken: maximum length of bone and of shaft; curvature of the shaft at ¼, ½ and ¾ of the distance along it; the least transverse and anteroposterior diameter of the shaft at these points; the least anteroposterior and superior-inferior diameter of the neck; and the angles which the neck, shaft and vertical axes make with one another. All linear measurements were in millimeters. The age, sex and race of the individual from whom the femur was obtained was recorded. All femora used were normal as far as known.

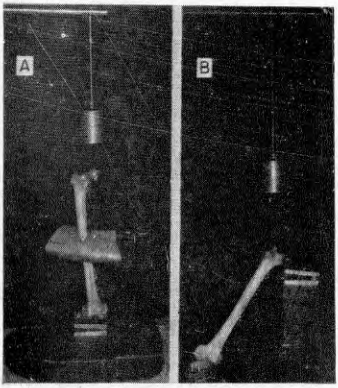

Fig. 2. Apparatus used in the dynamic vertical and "abduction" loading tests. The brass block, which is dropped upon the bone by burning through the supporting cord, weighs 7.9 pounds; the large steel block 160 pounds. The amount of energy dynamically applied to the bone is the product of the weight of the brass block times the distance through which it is dropped.—A. Dynamic vertical loading. The femur is held in a vertical position by passing it through an aperture in a piece of live rubber stretched over a ring attached to a stand. Its orientation was varied by means of an adjustable brass wedge placed beneath the distal end of the bone so that the infracondylar plane could be tilted from a horizontal position. See text for further explanation.—B. Dynamic "abduction" loading. Variations in orientation were obtained by resting the head on a series of steel and brass blocks so that it was raised higher above the floor. The brass block was dropped upon the greater trochanter but the distance through which it fell was varied.

The static vertical loading tests were performed by placing the bone in the testing-machine so that its infracondylar plane was horizontal and its long axis parallel with a vertical axis. This orientation was chosen as according to Walmsley (20), it closely approximates the position of the femur in the living body when standing erect with the knees and heels together. A vertical load was then gradually applied to the femoral head. One person operated the testing machine while the other watched the bone for the first appearance of cracks in the "stresscoat" lacquer. As soon as cracks were seen the machine was stopped and the load that had been applied was recorded. Sixteen such tests were run and the load at which the first cracks were noted varied from 400 to 990 pounds. One bone had a transverse fracture of the neck produced at a load of 1280 pounds but none of the other bones were loaded to failure. All of the others would undoubtedly have supported much greater weight before failure as the elastic limit of the "stresscoat" is far less than that of bone. Larger bones supported more weight before the appearance of cracks than did smaller ones. The same is also true of bones from individuals under 60 years of age as compared with those of older persons.

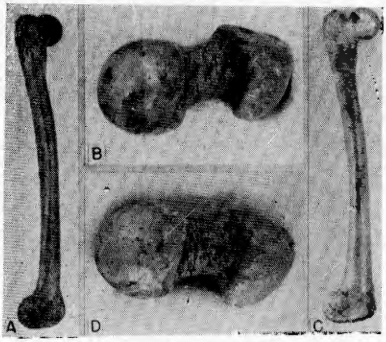

Fig. 3. Comparison of the "stresscoat" deformation patterns obtained by static and dynamic vertical loading of the femur of a 60 year old white male. In this and the following figures of deformation patterns some of the cracks in the lacquer have been traced with India ink for photographic purposes. Lacquer sensitivity 0.0012 inches per inch static loading; 0.0008 inches per inch dynamic loading. Static load-480 pounds; dynamic load-15.8 inch pounds of energy. — A. Deformation pattern on the shaft under static loading. — B. Deformation pattern on the neck under static loading. — C. Deformation pattern on the shaft unger dynamic loading. — D. Deformation pattern on the neck under dynamic loading.

Under static vertical loading the deformation pattern (Fig. 3 A, B) was located on the superior aspect of the neck and along the convex surface of the anterolateral aspect of the shaft. The same bones, in a similar orientation, were then tested under dynamic vertical loading. In these tests 15.8 inch pounds of energy dynamically applied to the head was sufficient to produce a deformation pattern (Fig. 3 C, D). Although the results of the two methods of testing can not be directly compared, since we are dealing with pounds in the static loading tests and dynamic energy in the dynamic loading tests, it is important to note that the deformation pattern was located on the same parts of the bone in each test, i.e. the superior aspect of the neck and the anterolateral aspect of the shaft. This means that those regions of the bone were under **tensile stress** while the opposite aspects of the bone were under compression.

Under static loading the first cracks were seen to appear on the superior aspect of the neck just distal to the head and on the anterolateral aspect of the shaft two or three inches distal to the area for the insertion of the gluteus minimus muscle. With increased load additional cracks appeared further along the neck and the shaft. The location of the first cracks to appear indicates the site of weakness where failure should occur under sufficient load. This was completely born out in the case of a transverse fracture of the neck (Fig. 4) which

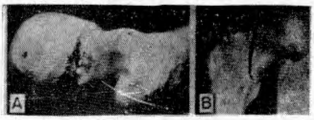

Fig. 4. Fracture of the neck of a femur produced by a static vertical load of 1280 pounds. — A. Superior view of the neck. Note that the fracture occurred at the site where it was predicted to be from the "stresscoat" pattern and that the fracture line is parallel with the cracks in the lacquer. — B. Anterior view of the head and neck.

occurred under a load of 1280 pounds just where it was predicted to be from the "stresscoat" deformation pattern. The fracture began on the superior aspect of the neck and gradually extended across the bone, parallel with the cracks in the lacquer, as the head of the femur and the rest of the bone was pulled apart. This means that the fracture was produced by **failure of the bone under tensile stress.**

The static vertical loading tests showed that the lateral condyle supports the greater share of the weight as it was crushed or slightly flattened while the medial condyle was not affected. That the femur behaves as an elastic body was also clearly demonstrated. In each test the bone could be seen to bend (Fig. 5) with increasing load and to return to its previous condition as the load was removed.

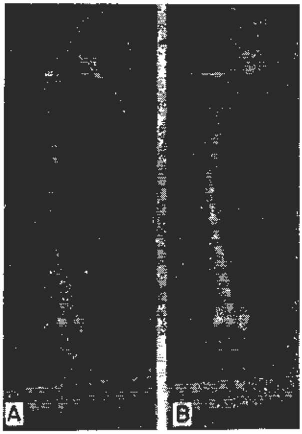

Fig. 5. Close-up view of a femur in the testing-machine. — A. The unloaded bone. Note that the white thread is taut. — B. The same bone under a static load of 650 pounds. Note the slack condition of the thread indicating the bending deformation of the femur. When the load was removed the bone quickly returned to its normal condition and the thread became taut again.

In order to determine the effect of slight variations in orientation of the bone tests were made with static and dynamic vertical loading of the head when the infracondylar plane of the bone made a 3° angle (opening laterally) with the horizontal plane. In this orientation the femur approximates its position when standing in the "normal" position of Fick (21) with the feet apart. This slight variation in orientation of the bone had no significant effect on the deformation patterns (Fig. 6) which were essentially similar to those obtained with vertical loading when the infracondylar plane was horizontal in position.

In both methods of testing the location and extent of the deformation pattern on the shaft were primarily determined by its diameter and curvature.

In the erect position of the body the femur may be compared with an eccentrically loaded column wich has a bending action superimposed upon a compression action. As a result of the bending, tensile stresses are developed on the convex side of the bent column, e.g the superior aspect of the neck and the anterolateral aspect of the shaft, and additional compression stresses on the concave side. That the femur behaves in this way was shown by the "stresscoat" defor-

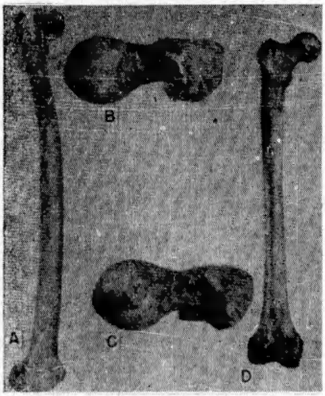

Fig. 6. Deformation patterns produced by dynamic vertical loading of the femur of a 49 year old Negro male. — A. Lateral view of the bone oriented so that the infracondylar plane made a 3° angle (opening laterally) with the horizontal plane. Energy expended 23.7 inch pounds. Lacquer sensitivity: 0.00105 inches per inch. — B. Superior view of the same deformation pattern. — C. Superior view of the same bone loaded when the intracondylar plane was horizontal in position. Energy expended 15.8 inch pounds. Lacquer sensitivity: 0.0008 inches per inch. — D. Lateral view of the same deformation pattern.

mation pattern. The magnitude of the tensile stress developed at any given point on the bone is dependent upon the size of the load, the diameter of the bone and the perpendicular distance of the given point from the load axis. The latter factor depends upon the size of the angles wich the vertical, the neck and the shaft axes make with one another. The compressive stress on the concave side of the bone is always greater than the tensile stress.

Other factors involved are that the femur is not of uniform diameter and that it is hollow. The latter is especially significant since a tubular structure, in proportion to the amount of material used, is the most efficient for resisting column action and bending stresses, just the type of forces most commonly acting on the femur in the living body. It should also be remembered that, according to Elftman (19), the muscles in the inferior extremity act so that the weight of the body is gradually applied to the femur during locomotion. This is important because the femur can support a greater load if it is gradually applied.

The angles which the neck and shaft axis make with each other and with the vertical axis also have an important bearing upon the vertically applied load the femur can support. The smaller the angle between the shaft and vertical axes and the larger the neck-shaft angle the greater the load that can be supported as the load axis is closed to that of the shaft. If the first angle were 0° and the second 180° the femur would be a straight hollow column, instead of a bent one, and concentrically loaded, instead of eccentrically. It would thus be in compression throughout. On the other hand, the larger the angle between the vertical and shaft axes and the more nearly the neck-shaft angle approaches 90° the smaller the load that could be supported without the sahft being strengthened in some way, e.g. thickened.

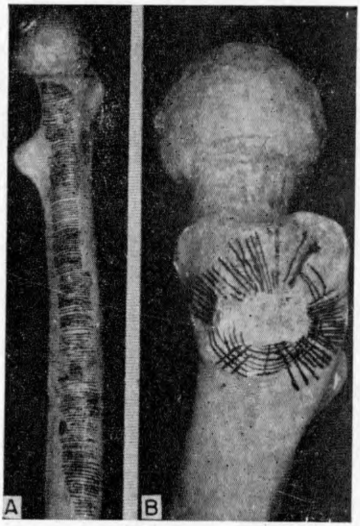

Fig. 7. An extensive deformation pattern produced by dynamic "abduction" loading of a femur of nuknown source. Energy expended 31.6 inch pounds. Lacquer sensitivity: 0.0008 inches per inch. — A. Medial view of the bone showing the deformation pattern on the inferior aspect of the neck and the medial aspect of the shaft. — B. The local deformation pattern obtained at the site of impact on the greater trochanter.

Static and dynamic loading tests were made of the bone in the "abduction" position, so named because it placed the inferior aspect of the neck and the medial aspect of the shaft under tensile stress as would occur if the femur were forcibly abducted with the proximal end relatively fixed. The load was applied to the greater trochanter, as may happen in the living body when a person falls. Preliminary tests showed that approximately 20 inch pounds of energy were required to develop a minimal deformation pattern. The bones from the right side had 23.7 inch pounds of energy applied to them and those from the left 31.6 inch pounds.

The first cracks appeared on the inferior aspect of the neck and with increased load gradually extended down onto the medial aspect of the shaft (Fig 7 A). In both regions the cracks were transverse to the long axis of the bone. The neck-shaft angle, probally because of minor variations in the orientation of the bone, apparently had little influence on the extent of the deformation pattern. However, evidence from the total weight of the bone and the length and thickness of the neck indicated that the degree of deformation varied inversely with the size of the mass to be moved.

In some cases a deformation pattern (Fig. 7 B) was also obtained on the greater trochanter. This pattern consisted of one set of cracks radiating from the point of application of the force and a second set forming incomplete concentric circles around the point. As the cracks represented a tensile stress perpendicular to their direction they indicate that the greater trochanter behaved as an indented rubber ball with both inbending (the concentric set of cracks) and direct tension (the radiating cracks) produced by the same force. Within the elastic limits of the bone the normal form was resumed after removal of the force.

A number of tests were also performed to demonstrate the effect of minor variations in orientation of the bone and the effect of loading to failure. In these tests the head of the femur was raised in stages from 73 mm. to 290 mm. above the floor and the energy applied was varied from 31.6 to 355.5 inch pounds. The patterns obtained were essentially similar to those previously described, additional evidence of the slight influence of minor variations in bone orientation. The explanation is that raising the head of the bone reduces the bending force on the neck but increases the compressive force on the shaft.

The location of the deformation pattern in these tests clearly demonstrated that the inferior aspect of the neck and the medial aspect of the shaft were under **tensile** stress. Furthermore, fractures

(Fig. 8) produced by static and dynamic loading of the bone in the "abduction" position again proved that the fracture arose from **failure of the bone under tensile stress.** In each case the fracture line started at the **site of greatest tensile stress,** just where it was predicted to be from the "stresscoat" pattern, and gradually extended through the bone.

Fig. 8. Anterior view of a fracture produced by "abduction" loading of a femur with 344.1 inch pounds of energy. The head of the bone was elevated 290 mm. above the floor and the load applied to the greater trochanter.

Static torsion loading studies were also made. Clamps held the bone in the testing machine by grasping the head and greater trochanter at one end and the condyles at the other. Because of the clamps the head, neck and greater trochanter moved as a unit. The axis of rotation passed through the shaft at the intercondylar and greater trochanteric levels. In each test the trochanter was rotated medially to simulate lateral rotation of the thigh with the proximal end of the femur fixed. The indicator on the torsion machine recorded the torque in units of 8.3 inch pounds of torque. One inch pound of torque is the twisting movement produced by one pound of force acting at one inch from the center of rotation.

During the tests the torque was gradually applied until cracks in the lacquer were noted. An attempt was made to produce minimal, moderate and extensive deformation patterns (Fig. 9 A), but in a few cases the cracks were difficult to see and the bone was loaded to failure before the pattern was noted. However, the patterns were clearly visible after the bones had been etched with the dye.

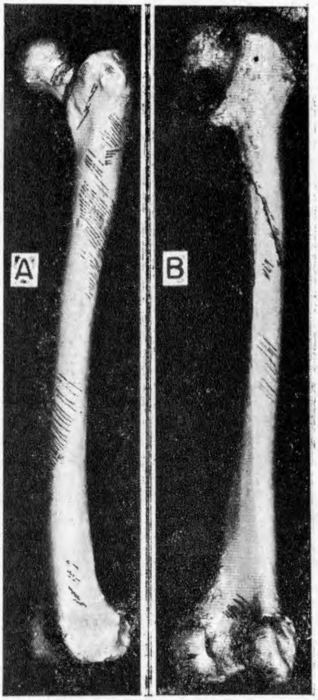

Fig. 9. A. A well defined torsion deformation pattern produced by 514.6 inch pounds of torque statically applied. Note that the individual cracks in the pattern lie at a 45° angle to the long axis of shaft and that the entire pattern spirals around the bone at a 45° angle to it. — B. Example of a torsion fracture produced in the femur of a 60 year old white male by 282.2 inch pounds of torque statically applied. Note that the fracture line is parallel to the cracks in the "stresscoat" pattern and that it takes a spiral course around the shaft at a 45° angle to its long axis.

The first cracks invariably occurred in the neck at a 45° angle to its long axis. The next cracks appeared on the shaft, just distal to the greater trochanter or on the distal part of the shaft. These cracks also lay at a 45° angle to the long axis of the bone. In the extensive patterns produced by heavier loads the cracks spiraled around the length of the shaft at a 45° angle to its long axis.

The fractures produced by torsion loading occurred at the proximal end of the shaft and took a spiral course around the shaft following the direction of the **tension** lines of the cracks. The appearance of the "stresscoat" pattern proved that the torque produced a **tensile strain** in the bone. As the first cracks appeared on the neck, that region should have failed first but it was prevented from doing so by the clamp holding it. Both the anterior and posterior aspects of the neck were placed under **tensile** strain, as indicated by the cracks in the lacquer, because the force was applied to the anterior aspect of the head and the posterior aspect of the greater trochanter. However, the deformation was small and could not go beyond the elastic limit of the bone because of the clamp.

According to mechanical principles **torsion produces tension** along a spiral line around the center of rotation. Furthermore, the spiral line makes a 45° angle with the horizontal plane when the axis of rotation is vertical. This was beautifully demonstrated by the extensive torsion patterns which spiraled around the shaft of the bone at a 45° angle to its long axis. The tensile strain is oppsed by a compressive strain in the opposite direction and at a 90° angle to the former. Rauber (1) showed that bone is weaker in tension than in compression, and consequently, when subjected to increasing amounts of equal tension and compression, it **fails under tension stress.** This is completely confirmed by the fractures produced with torsion loading (Fig. 9), the fracture line taking a **spiral course along the lines of tensile strain** as indicated by the "stresscoat" deformation pattern. The extent of the pattern varied inversely with the mass of the bone and after the appearance of a fully developed pattern a little additional energy was sufficient to produce failure.

The spiral torsion fracture is thus just another type of fracture resulting from **failure of the bone under tensile stress**. It is not entirely distinct from bending failure as far as the influence of tensile stress is concerned and does not arise from failure under shearing stress.

The negligible effect on the deformation pattern produced by variations in the orientation of the bone, which were quite marked in some of the "abduction" tests, is interesting in view of all that has been published on bone orientation and fracture. This is not surprising, however, when one considers the factor of safety in the construction of the femur. This factor, according to Koch (4), is 5.68 for running, 11.36 for walking and 30.30 for standing. In each case the figures were based on the maximum values of the ultimate strength of bone. The femur is built to endure violent bending and twisting action such as occurs in the living body. Before marked deformation or failure takes place the magnitude of the force must be very great or its action line must form an acute angle with the bone.

In the living body during locomotion each femur alternately supports 93% of the total body weight, i.e. all the weigth except that of the leg and foot of the supporting limb. It is also subjected to a variety of stresses of varying magnitude and direction as a result of postural changes of the bone and the effect of muscles and ligaments. All these forces influence the behavior of the living femur and their deformation effects would be added to those produced by vertical loading.

In the dinamic loading tests essentially all of the energy expended was directly absorbed by the bone, the amount absorbed by the brass and steel blocks being negligible. This is somewhat different from the conditions existing in the living body where, during locomotion, a considerable amount of the energy is absorbed by the ground as well as by muscles, ligaments, intervertebral discs, cartilages and other bones before it reaches the femur. However, the fact that relatively light loads dynamically applied produced well defined deformation patterns may be a clue to the nature of fractures resulting from violent muscular action.

Another important point demonstrated by the tests is that each type of loading produced a characteristic deformation pattern. Thus, from an examination of the pattern one can deduce the general point of application of the force or, conversely, if the point of application of the force is known one can predict the location and type of the resulting deformation pattern. The former fact might be of assistance in designing protective clothing or gear, the latter of particular help to the raidologist in locating a suspected fracture arising from a blow at a known point.

The most significant result of the tests was the proof of the importance of **tensile stresses** in the fracture mechanism. In both the skull and the femur all the linear fractures produced in the tests, regardless of the experimental conditions, arose from **failure of the bone under tensile stress.** As shown by Rauber (1) the tensile strength of bone is less than its compressive strength and decreases more rapidly with age, an important factor to be considered in accounting for the greater incidence of fractures in elderly people. The importance of **tensile stresses** in the fracture mechanism has not been generally recognized in the past although it had been discussed by Rixford (22). Indeed, Homans (23) is one of the few surgery textbooks that includes any discussion of the mechanism of fracture.

In conclusion the results of the above discussed tests may be summarized as follows:

1. Under static and dynamic vertical loading the femur may be considered as an eccentrically loaded hollow column in which a bending action is superimposed upon a compression action. The bending action gives rise to **tensile stresses,** indicated by the cracks in the "stresscoat" lacquer, upon the convex side of the bent column, i.e. the superior aspect of the neck and the anterolateral aspect of the shaft, and additional compression stresses on the concave side.

2. The first cracks appear on the superior aspect of the neck just distal to the head and on the lateral aspect of the shaft two or three inches distal to the insertion area of the gluteus minimus muscle. With increased load the pattern gradually extends distally along the neck and the shaft.

3. In all cases the cracks in the "stresscoat" lacquer arise from **tensile stresses** in the underlying bone and lie transverse to the direction of these stresses.

4. The anatomical factors influencing the strength of the femur under vertical loading are: the size of the bone, the diameter of the neck and the shaft, the curvature of the shaft and the angles which the shaft, neck and vertical axes make with one another. Other factors are the age and sex of the individual.

5. The static vertical loading tests clearly demonstrated that the femur behaves as an elastic body.

6. Static torsion loading produced a tensile deformation pattern which spiraled around the shaft at a 45° angle to its long axis. The individual cracks in the lacquer also lay at a 45° angle to the long axis of the neck and the shaft.

7. Static and dynamic "abduction" loading produced tensile deformation patterns on the inferior aspect of the neck and the medial aspect of the shaft indicating that those regions of he bone were under tensile stress. Local deformation patterns were also obtained at the site of impact, e.g. the greater trochanter.

8. Variations in the orientation of the bone had little effect on the location of the deformation pattern. The same is true of the results obtained with static and dynamic vertical loading of the femoral head.

9. Each method of loading produced a characteristic deformation pattern.

10. The fractures produced by the different tests occurred where they were predicted to be from the "stresscoat" deformation pattern and followed the course of the tensile stress as indicated by the pattern.

11. In both the skull and the femur the fracture line began at the site of the first appearance of the "stresscoat" cracks and ran parallel with the direction of the cracks. This means that the fracture started at the site of **highest tensile stress** and arose from **failure of the bone under tensile stress.**

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